Army Research Laboratory

The Use of Multiple Unmanned Ground Vehicles (UGVs) for Unexploded Ordnance (UXO) Remediation at White Sands Missile Range

by Alejandro Góngora

ARL-TN-297 November 2007

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14. ABSTRACT
This project studied the possibility of using automated unmanned ground vehicles (UGVs) for unexploded ordnance (UXO) clearance at White Sands Missile Range (WSMR), NM. Various multiple-vehicle integration systems and search techniques were investigated and the basic UXO gathering system (BUGS) performance was analyzed. The use of a BUGS-like system was recommended for use at WSMR's Phase II impact areas, as well as for further research on search techniques and mobile platforms in a desert environment.

15. SUBJECT TERMS
UXO remediation, UGV, WSMR impact areas, search techniques, BUGS

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1. Introduction

The presence of unexploded ordnance (UXO) at White Sands Missile Range (WSMR), NM, is a problem that has already claimed a life. In addition, current UXO clearance procedures expose members of WSMR's 734th Ordnance Company to unnecessary risk.

By far, the highest concentration of UXO is found in the areas of projected missile impacts. These areas are where smart munitions/smart submunitions (SM/SSM), as well as multiple cargo submunition systems, are tested. Some of these areas are also known as warhead impact targets (WITs). Occasionally, submunitions are deployed outside their projected impact areas requiring a thorough search to find and neutralize these UXOs in order to reduce risk to WSMR personnel.

Impact areas are grouped in two distinct categories: Phase I and Phase II. Phase I impact areas are where submunitions with an inert main charge are tested. Some of the submunitions tested in these areas can have live detonators in the fusing system. Phase I impact areas are kept in a mowed grassland condition. The Phase II impact areas are where live submunitions are tested (*1*). These areas are kept in a bladed condition, or at least an area of about 574 acres in the middle. Table 1 shows the total square footage of each missile impact area at the range.

Table 1. WSMR's impact areas.

Impact Area	Munition Type	Area Diameter (ft)	Grid Size (ft square)
G-10	Phase I	4,200	300
G-16	Phase I	4,200	300
G-20	Phase I	8,000	300
G-25	Phase I	7,000	100
ABC-1 WIT	Phase I	5,000	100
Pup WIT	Phase I	10,000	200
649 WIT	Phase I	9,400	300
Denver WIT	Phase II	10,000	100
Rhodes WIT	Phase II	10,000	100
Stallion WIT	Phase II	10,000	100

The submunition pattern area size depends on the height of burst of the rocket or missile, but it is generally a circle between 500 and 600 ft in diameter of uniformly distributed submunitions. A conservative dud rate is 5%. The number of submunitions can vary from roughly 300 up to 800, depending on the delivery system and its configuration. Figure 1 shows an aerial photograph of Stallion WIT and the approximate size of the submunition pattern area.

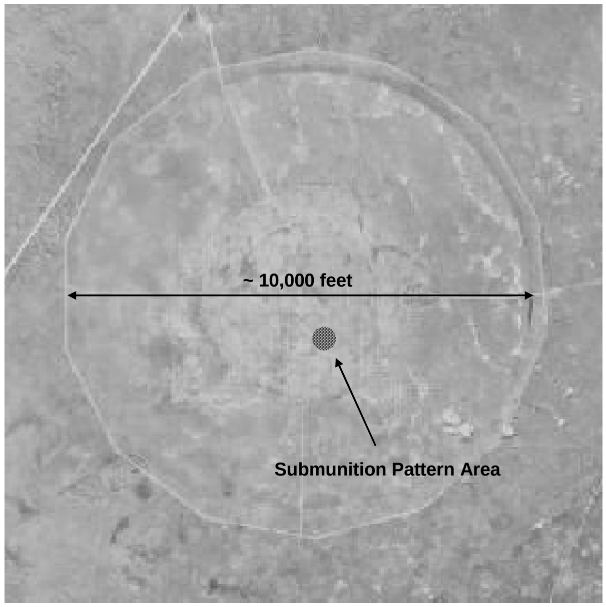

Figure 1. Submunition pattern area.

2. Goal

The goal of this project is to investigate the concept of using an unmanned ground vehicle (UGV) system for UXO clearance at WSMR, NM, in particular at the Phase II impact areas, to reduce the risk of injury or death to Explosive Ordnance Disposal (EOD) personnel.

3. Current Procedures

Current clearance operations (i.e., surface sweeps) of Phase II impact areas start with a visual reconnaissance of the area by the Warheads Test Branch personnel. When a UXO has been visually identified, it is surveyed and a flag is placed near it so its location can be easily seen. Then, the 734th Ordnance Company, knowing the location of each UXO by its flag, places a block of explosives to blow it up in place (BIP) by means of a sympathetic explosion. Unless failure analysis of the ordnance is necessary, most UXO are BIP. The cost of a surface sweep operation is roughly $110.00 dollar per Soldier per day. Approximately three to six individuals are needed in these clearance operations.

4. Possible Solutions

A group of multiple UGVs can substitute for EOD personnel for BIP or pick up and carry away (PUCA) operations. Multiple low-cost UGVs are preferred over a single more expensive platform, because there is a "…minimization of probability of mission failure, the adaptability and reusability of system components, and the increase of operation speed." (*2*)

A multiple UGV system can be integrated as autonomous or semi-autonomous. An autonomous system is a singular group of either independent or interdependent robots. A semi-autonomous or "assisted" UGV system can have an operator control unit (OCU) and/or an assisting reconnaissance asset.

The singular group of independent UGVs can be developed with off-the-shelf detection, control, and navigation systems. "This approach simplifies the system design by ignoring the communication, interaction, system integration, etc. (*2*)" A singular group of interdependent robots can work as a team to complete the clearance mission more effectively, but they will certainly require more hardware and software integration and a communication system, thus increasing its complexity and cost (*2*). An OCU "can create a global picture of the mission area for the entire robot group to reference. Information from individual robots or from an assisting reconnaissance asset can be assimilated into a global map or information for the user or the other robots …The control station can quickly create new information, such as obstacle location, UXO location, safety areas, and/or searched zones. The control station can also keep track of such information as vehicles' location, vehicles' path, unsearched areas, etc. Through visual tracking or map building, the OCU can help increase the overall effect on UXO clearance operations" (*2*).

Finally, an assisting reconnaissance asset, which can be a specialized UGV, can be used to perform a quick area survey to provide target locations either directly to the UGV units or through an OCU (*2*).

Multiple UGV systems can carry out various types of search techniques depending on whether the approximate UXO location is known or not. If the UXO location is not known, a multiple UGV system can perform a random search, an exhaustive search, or a dynamic zone allocation (DZA).

Random search consists of a random change in heading after some time delay (*3*). Even though random search is considered the lower bound of detection probability (*4*), it is not the worst search strategy, not moving is worse. An example of a random search is shown in figure 2.

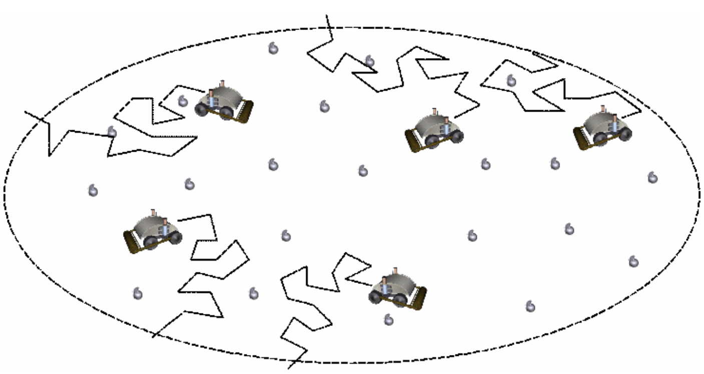

Figure 2. Example of a random search.

Exhaustive search, also known as coordinated or area pattern search, is realized when the UGV system follows a lawnmower or spiral pattern (figure 3). This type of search requires a very accurate navigational system (comparable to the UXO sensor sweep width) and a heading error of less than ± 10° (*5*) before its performance degrades to that of random search.

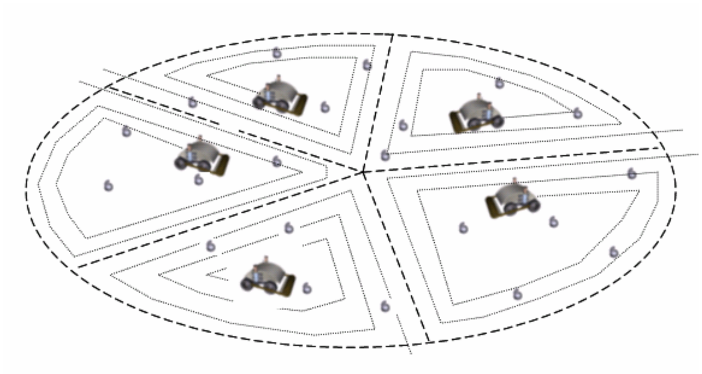

Figure 3. Example of an exhaustive search.

DZA is a search technique used to efficiently find targets that may be encountered in clusters within a larger area. An advantage of DZA is that a maximum number of targets can be found in a limited amount of time. The robots disperse and randomly search for targets. As one target is found, it is assumed to be part of a cluster, and the location is designated as the center of a dynamic zone (DZ). Other available searchers are summoned to the newly defined DZ to perform random searches within the zone. As additional target is found within DZ, the location is designated as the center of a new DZ. (*6*)

An example of DZA is shown in figure 4.

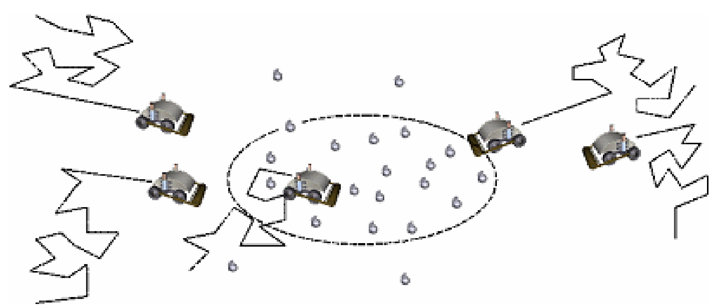

Figure 4. Example of a DZA.

When the UXO's exact or approximate location is known, a direct search can be implemented (figure 5). Direct search consist in downloading the exact or approximate target location information directly to the UGV units or by means of an OCU. If the UXO location is approximate, the UGV is expected to execute a random search within a small area. The use of a shared target list, where all UGVs can operate on all targets by searching for the closest one on the list, can enhance the direct search approach.

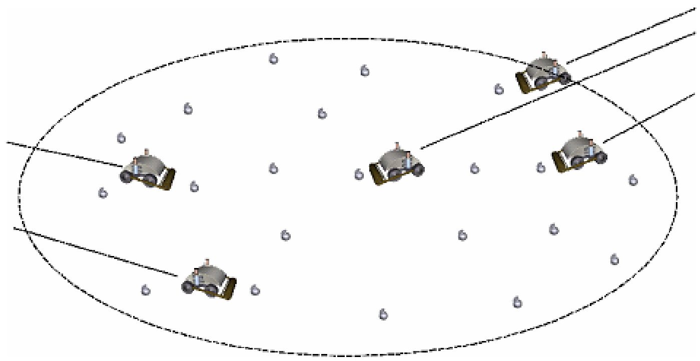

Figure 5. Example of a direct search.

If a random search technique is the method of choice for a certain UGV system, it can be realized using a singular independent group of UGV. No interaction between the individual UGVs is essential; they can treat each other as obstacles. A DZA requires communication between the UGVs. Exhaustive search requires coordination between the UGVs so that each vehicle can perform a pattern search in its own area. Table 2 shows the integration systems discussed earlier that support the different search types.

Table 2. Integration systems that support the different search modes.

	Singular Group		**Assisted Group**	
Search Mode	**Independent**	**Interdependent**	**OCU**	**Reconnaissance Asset**
Random	x			
DZA		x		
Exhaustive		x	x	x
Directed			x	x

Given a search within an area A, the detection rate α is a function of the vehicle's speed U_o, the UXO sensor's probability of detection p and radius r, and the number of vehicles N_v involved in the search:

$$\alpha = U_o(2r)\,pN_v / A \tag{1}$$

The detect fraction, or detection probability using random search D_r, is determined by the detection rate α and time t in the following relationship:

$$D_r = 1 - e^{-\alpha t} \tag{2}$$

The following plot (figure 6) shows the random search detect fraction using various numbers of UGVs in a circular area of 500 ft in diameter (18,242 m^2), such as the average submunition pattern area. The vehicle speed is assumed to be 0.5 m/s, the sensor detection radius 20 cm, and the probability of detection of sensor 100%, with no obstacles.

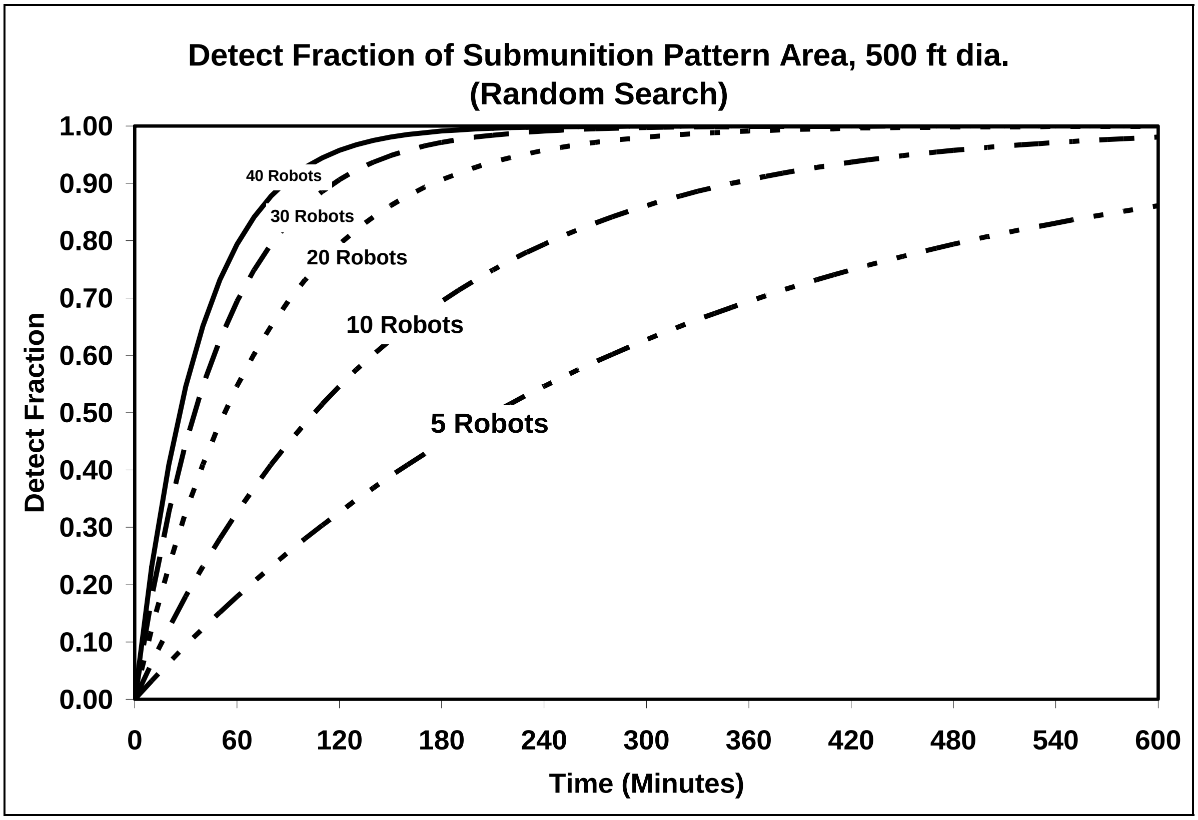

Figure 6. Random search's detect fraction of submunition pattern area.

Healey and Kim (*6*) worked on a series of computer simulations of PUCA scenarios and obtained the plot shown in figure 7. The operating area for these simulations is a 150-by-150 m square (22,500 m^2), which is numerically close the submunition pattern area. There are 3 randomly placed clusters (circular in shape and 25 m in diameter) of approximately 33 targets each, plus another 33 targets randomly distributed over the whole area with the total of about 130+ targets, a number close to the number of dud submunitions expected in a multiple rocket system. There are also randomly occurring obstacles. The vehicle speed is assumed to be 0.47 m/s, the sensor detection radius 19 cm, and probability of detection of sensor 100%. Ten vehicles were used in this simulation.

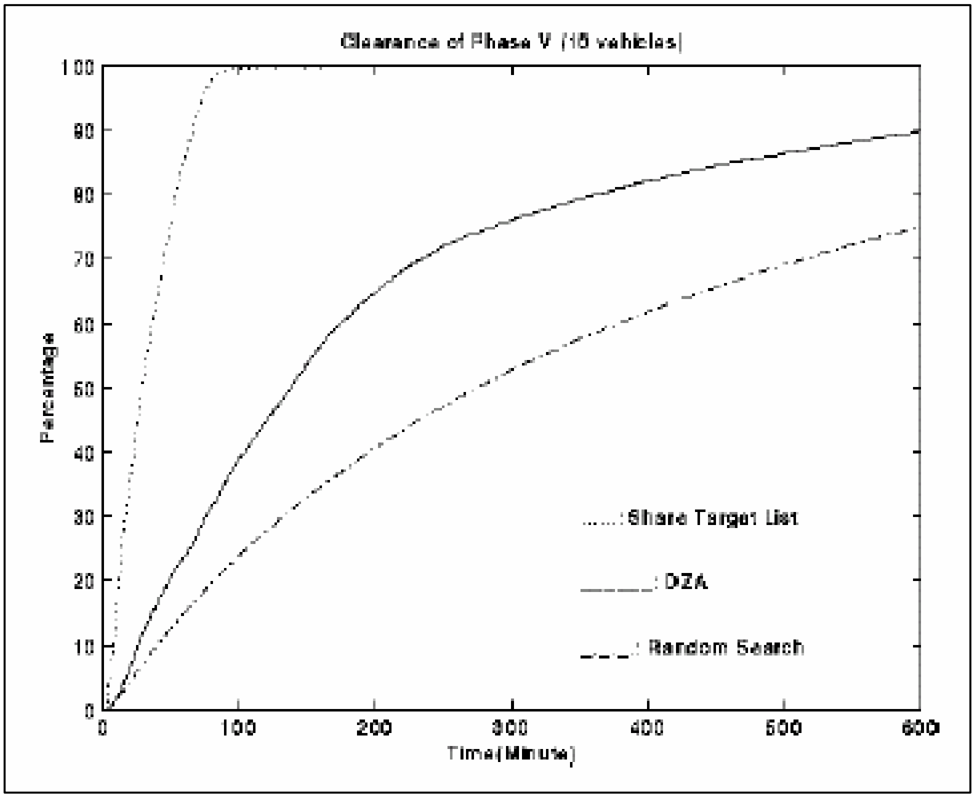

Figure 7. Comparison between random search, DZA, and shared target list.

As can be observed from the plot in figure 7, when the location of the UXO is known, using a shared target list, the operation time is drastically reduced. Figures 6 and 7 show that, for the area size described, randomized search cannot be realized due to electrical power limitations with off-the-shelf battery technology. Fifty or more UGVs would be required to complete an operation before their batteries run down.

At WSMR, NM, most of the UXO are BIP, so it can be expected that the lack of a PUCA round trip will further reduce the operation time and, therefore, decrease the number of UGVs needed for the operation.

The Navy's EOD technical division (NAVEODTECHDIV) was involved in the development of the basic UXO gathering system (BUGS) to demonstrate a proof of concept system. The emphasis was on UGV behavior algorithms in a PUCA scenario since it was thought that if a UGV can PUCA, it would certainly be able to place a small charge near a UXO (BIP) as stated in the General Dynamics Robotics Systems (GDRS) final report (*7*).

Two systems were developed: an in-house system and a contracted system. The in-house system, or NAVEODTECHDIV "BUG", is a fully autonomous system designed to execute a random search. The contracted system was developed by GDRS as a semi-autonomous system capable of executing an area pattern search or a direct search with the help of an OCU. Figure 8 shows the GDRS BUGS's self-explanatory block diagram from the final report (*7*).

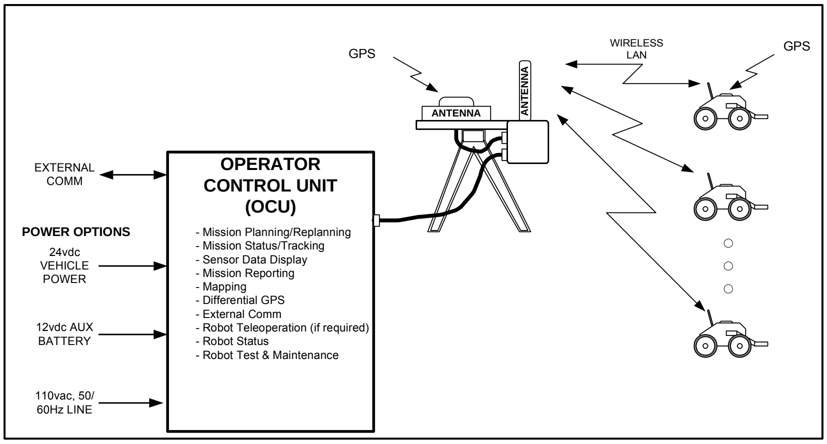

Figure 8. The GDRS BUGS block diagram.

The results obtained after multiple weeks of testing are shown in table 3 (*8*).

Table 3. BUGS tests results.

Method	Condition	UXO per Hour
8-man USMC EOD team in PUCA mission	3103 UXOs gathered in 4 days, including 2 short days (6 h = 1 full day)	20 per man
NAVEODTECHDIV BUGS, random search	4 robots in 100 by100 ft area with 100 targets, 80% coverage	6 per robot
GDRS BUGS, direct search	4 robots in 100 by 100 ft area with 100 targets, known locations	15–25 per robot
GDRS BUGS, direct search	4 robots in 100 by100 ft area with 100 targets, unknown locations	10–20 per robot

As can be seen from table 3, the GDRS BUGS in a directed search mode has an approximate median of 20 UXO cleared per hour (PUCA), which corresponds to an EOD Soldier's clearance performance.

The following procedure is for a direct search if a system such as the GDRS BUGS is used at WSMR, NM:

- Warheads personnel visually inspect the area and tag each UXO location with a handheld global positioning system (GPS) device.
- EOD personnel set up the UGV system with OCU at a safe distance from the operation area.
- GPS data is downloaded to the OCU computer.
- UGVs are sent to neutralize UXO.

Possible mobile platforms for the UGVs include wheeled, tracked, and legged. Wheeled platforms are preferred for harder terrain. Tracked vehicles have been the platform of choice for soft terrain, but recently legged mechanisms have been considered as an environmentally friendlier alternative because of their smaller footprint. In fact, a smaller footprint gives "more local pressure for the same weight vehicle and better traction in soft ground. This is because the walking motion puts weight on the driving leg and increases available frictional shear loads (*5*)." A "high stepper" UGV (figure 9) can walk over obstacles and might be able to detect UXO under small bushes for near-surface UXO cleanups.

Figure 9. A "high stepper" UGV.

5. Findings

This study found that the GDRS BUGS using a shared target list approach (direct search) can be implemented in an area of similar dimensions and submunition density as the Phase II impact areas assuming optimal terrain conditions. The GDRS BUGS mobile platform will probably make the system less efficient at WSMR's impact areas due to its limited uneven terrain capability.

It is not yet clear how continuous obstacle avoidance due to heavy vegetation (non-bladed areas) can affect the GDRS BUGS algorithm performance.

6. Recommendations

My short-term recommendation is to develop a GDRS BUGS-like UGV system with more rugged characteristics and the capability to negotiate bladed, semi-flat terrain found at WSMR's Phase II impact areas. I further recommend the following:

- Investigate the impact of desert vegetation (i.e., continuous obstacle avoidance) and adverse terrain conditions on performance for all search strategies.

- Develop legged or tracked vehicles to negotiate heavily vegetated desert terrain.

- Investigate power sources for UGVs other than batteries for large area and/or long time search requirements.

7. Costs

The expected cost target of a reliable UGV system is $3,900 per unit and $26,500 for the OCU (*7*)*. The total cost of 15 UGVs and the OCU would be $85,000, assuming NAVEODTECHDIV shares information under a non-commercialization agreement and the cost target is realized. An extra $110,000 for research and development would be required if the UGV system's reliability, maintainability, and performance must be increased to satisfy more of what is currently envisioned.

It is estimated that each EOD UXO cleanup operation at the Phase II impact areas costs about $1,100. Assuming there are two missions per month at WSMR, NM, the approximate total cost per year would be $26,400. If the cost target for the UGV system can be reached, its cost would correspond to the cost of about three years of current EOD cleanup operations, which is small price to pay for the increased safety of EOD personnel. The estimated cost of further research and development on system integration, mobile platforms, and power sources is $330,000.

8. Conclusions

This report presented integration systems and search strategies using UGVs for UXO remediation at WSMR, NM. The performance of the BUGS was analyzed. It was found that the GDRS BUGS' shared target list algorithm can be efficiently used to BIP or PUCA UXO, but that a more rugged version would be required to operate at the Phase II impact areas. More research was recommended to increase mobility and endurance in a desert environment.

* $23,000 adjusted for inflation.

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Acronyms

BIP	blow it up in place
BUGS	basic UXO gathering system
DZ	dynamic zone
DZA	dynamic zone allocation
EOD	Explosive Ordnance Disposal
GDRS	General Dynamics Robotics Systems
GPS	global positioning system
NAVEODTECHDIV	Navy’s EOD technical division
OCU	operator control unit
PUCA	pick up and carry away
SM/SSM	smart munitions/smart submunitions
UGVs	unmanned ground vehicles
UXO	unexploded ordnance
WIT	warhead impact target
WSMR	White Sands Missile Range

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